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Emerging Applications of Synchronous Ethernet in Telecommunication Networks

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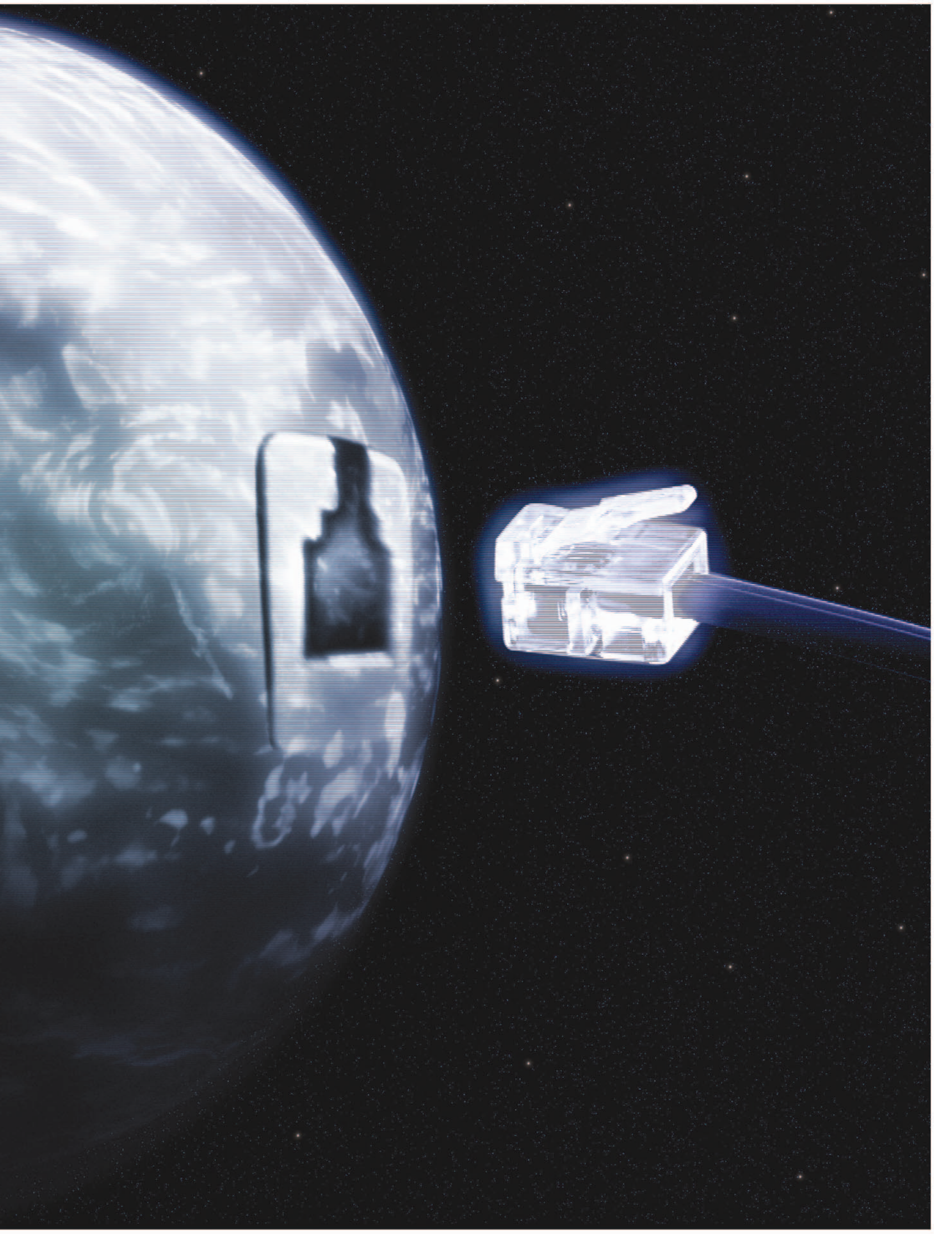

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Abstract

The current rising demand for broadband services calls for network technologies that deliver significantly lower cost-per-bit than traditional TDM networks. Ethernet, in particular carrier-grade Ethernet technologies (as defined in the Metro Ethernet Forum (MEF) and ITU-T standards), is now being deployed by Telecom service providers from the core to the access. However, given that many of these broadband services require precise synchronization for efficient operation, the distribution of timing signals over Ethernet has become just as critical as the data that it carries. Synchronous Ethernet (Sync-E), defined in a suite of ITU-T Recommendations, provides a method of distributing frequency over Ethernet links. ITU-T Recommendations G.8261, G.8262, G.8264 (which define Sync-E) indicate that synchronization can be achieved over Ethernet links by synchronizing the bit clock of the physical layer as is currently done on SONET/SDH links. In this paper, we describe applications which harness one of the main attributes of Sync-E, which is essentially native Ethernet equipped with point-to-point distribution of timing signals. By enabling point-to-point distribution of timing signals from an accurate timing reference source, Sync-E aims to bring carrier grade telecom quality clocks to packet networks. The paper also discusses some emerging applications of Sync-E, particularly, those applications that can exploit both the high data carrying capacity and clock distribution attributes of Sync-E.

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1. Introduction

Communication networks are currently evolving towards packet based cores with various forms of multi-service devices located at the network access and edge points. Many service providers and carriers are now actively deploying Ethernet as the data transport mechanism in their core networks, and as transport medium in either the access or backhaul segments of their networks. In most scenarios, the networks being deployed have a packet switched core, some form of backhaul connectivity from core to multi-service access and edge devices, and access connectivity to the customer devices and networks. The multi-service devices typically deliver a mix of TDM type services and packet based services.

The need to distribute an accurate reference timing signal (be it from a Building Integrated Timing Supply (BITS), GPS, or standalone atomic clock) through such packet based cores will still exist because of the need to interwork with existing TDM devices (e.g., SONET/SDH network elements) and networks, and also because of the need to maintain accurate synchronization to wireless base stations and switching center devices. The main challenge is to distribute timing signals of specified quality through the packet switched network down to the access and edge equipment. Currently native Ethernet (IEEE 802.3) is asynchronous with no timing traceability to a reference clock. However, the asynchronous nature of Ethernet provides certain transmission challenges such as distribution of timing signals, synchronization of network elements, and defining an effective synchronization network architecture.

Within the Telecom industry and standards groups, timing distribution and clock synchronization fall under two broad categories, namely, Layer 1 methods (Figure 1a) and Layer 2 and higher methods (Layer 2+) of the OSI model of communication as shown in Figure 1b. The Layer 1 (e.g., Sync-E, PDH, SONET/SDH), and Layer 2+ methods (e.g., NTP [1], IEEE 1588 PTP [2]) differ mainly in the method used to inject and transport synchronization over the network from a reference clock. Layer 1 methods achieve synchronization via the physical layer bit stream while the Layer 2+ methods do so via differential clocking [3]–[7], processing transmitted clock samples encoded within the packets from a transmitter to a receiver [8], or processing packet arrival patterns at the receiver to generate timing signals [9]–[12].

For packet networks, one of the important Layer 1 methods identified and currently catching on fast in the Telecom industry is Sync-E [13]–[15]. Sync-E implements timing similar to what is seen in traditional TDM networks (e.g., PDH, SONET/SDH)—the physical layer of an Ethernet link is used to deliver timing from one end of the link to the other. Timing transfer is achieved by enslaving the downstream link's Ethernet physical layer clock to the upstream's clock. The obvious advantage of this approach is that, by relying on the physical layer only, clock synchronization quality is not influenced by impairments introduced by the upper layers, namely, packet delay variation (PDV), packet losses, and out-of-order arrival of packets at their destinations.

2. What Is Synchronous Ethernet?

Until recently, synchronization has primarily been distributed to telecommunications network nodes using TDM links—DS1 links in North America and E1 links in Europe and other parts of the world. The primary TDM standards related to synchronization for both plesiochronous digital hierarchy (PDH) and synchronous digital hierarchy (SDH) networks are as follows. The jitter and wander specifications of PDH interfaces are given in G.823 [21] and G.824 [22]; G.811 [23] specifies the reference clock of digital networks; G.810 [24] provides the definitions related to synchronization in TDM networks. For SONET/SDH, the definition of slave clocks is provided in G.812 [25] (for Synchronization Supply Unit (SSU)) and in G.813 [26] (for SDH Equipment Clock (SEC)). G.825 [27] specifies the jitter and wander of STM-N interfaces, and the SDH synchronization layer is specified in G.781 [28].

The evolution of communication networks toward packet-based technologies has increased interest in the distribution of synchronization over packet networks. To address the challenges posed by migration of communication networks from TDM to a packet network architecture, a number of standards bodies including the ITUT have been defining specifications to enable synchronization signals to be transported accurately across packet networks. Work in ITU-T Study Group 15, Question 13 (Q13/15) resulted in a number of specifications some which define Sync-E. The Sync-E specifications and requirements are defined in the following primary standards:

- **ITU-T Recommendation G.8261 [13]:** G.8261 discusses the challenges in TDM-packet interworking, circuit emulation services (CES), and synchronization transport over packet networks including related issues like wander budget definition and performance characterization in the presence of packet delay variation (PDV). G.8261 also

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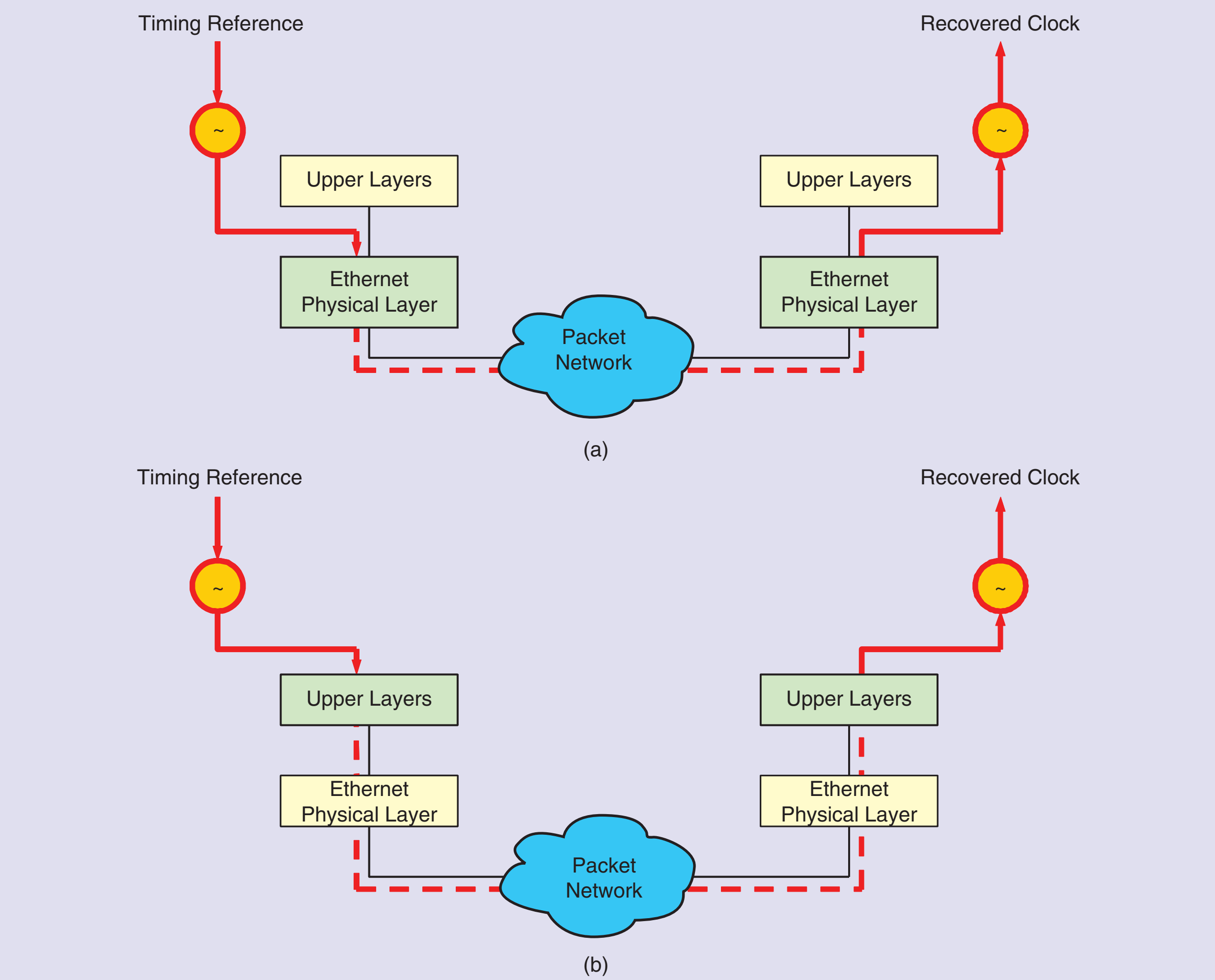

Figure 1. Frequency distribution methods. (a) Frequency distribution via Layer 1 (e.g., Sync-E, PDH, SDH/SONET). (b) Frequency distribution via Layer 2+ (e.g., NTP, IEEE 1588 PTP).

describes functions that are applicable to the different modes of CES (network-synchronous solutions, and differential and adaptive methods) and provides guidance on the deployment of synchronization solutions. Annex A of G.8261 defines the network architecture for Sync-E. This work extends the scope of the G.803 [29] reference synchronization chain to Sync-E equipment. G.8261 defines the concept and performance characteristics of Synchronous Ethernet Equipment Clocks (EECs).

- **ITU-T Recommendation G.8262 [14]:** G.8262 specifies the clocks for Synchronous Ethernet equipment. The specifications are done to ensure that Synchronous Ethernet clocks are compatible with SONET/SDH clocks as defined in G.813 [26] and G.812 [25]. G.8262 defines requirements for clock accuracy, noise transfer, holdover performance, noise tolerance, and noise generation. G.8262 also provides mask plots specifying the accuracy of wander and jitter using mean time interval error (MTIE) and time deviation (TDEV) values over various observation intervals.
- **ITU-T Recommendation G.8264 [15]:** G.8264 specifies the use of synchronization status messaging (SSM) within Sync-E networks. SSM allows the source traceability of the clock to be signaled to downstream devices. Indication of SSM Quality Level (QL) of the clock driving the synchronization chain allows the network to control/maintain/restore the synchronization chain and to prevent timing loops and propagation of bad quality clock signals. SSM as well as the newly defined Ethernet Synchronization Messaging Channel (ESMC) allow Sync-E to interwork with existing SONET/SDH infrastructure by allowing the Sync-E links to convey the SSM quality level defined in G.707 [30] and G.781 [28].

Table 1.
Key elements of synchronous Ethernet specifications and requirements.

Item	Key Elements
Synchronous Ethernet in General	■ Transport a reference frequency via the Ethernet physical layer (which is not impacted by PDV). Based on well-established SDH/SONET synchronization model (ITU-T G.813 clock model) ■ Reuse SDH/SONET principles to allow Sync-E to interwork with SDH/SONET network ■ Ensure interworking with native Ethernet (IEEE 802.3) equipment (no impact on IEEE 802.3 standard) ■ Sync-E does not support phase/time synchronization
ITU-T Rec. G.8261	■ Sync-E architecture defined in Annex A ■ Defines synchronous Ethernet equipment clock (EEC) ■ Network limits based on SDH/SONET
ITU-T Rec. G.8262	■ Defines two options for EEC: • EEC Option 1 for G.813 Option 1 which applies to Sync-E equipment designed to interwork with networks that operate in the 2048 kb/s hierarchy (SDH networks) • EEC Option 2 for G.812 Type IV which applies to Sync-E equipment designed to interwork with networks that operate in the 1544 kb/s hierarchy (SONET networks) ■ Specifies clock parameters as for G.813 ■ Full compatibility with the G.803 SDH reference chain ■ Mix of SEC and EEC can be done in the G.803 SDH reference chain ■ Specifies Sync-E, STM-N and PDH as interfaces for EEC
ITU-T Rec. G.8264	■ Defines frequency transfer using Sync-E: General information and operational modes (synchronous and non-synchronous) ■ SSM for Sync-E: • Defines Ethernet synchronization messaging channel (ESMC): • SSM quality level (QL) is conveyed over Ethernet over a specific channel based on IEEE 802.3, organization specific slow protocol (OSSP) • ESMC protocol is composed of the standard Ethernet header for a slow protocol, an ITU-T specific header, a flag field, and a type length value (TLV) structure • Currently defines two messages, event and information, both supporting the mandatory QL TLV for SSM transmission • Event and Information messages defined to meet performance requirement for reference switching in G.781 • SSM QL data is mapped into a TLV format • ESMC protocol allows for future enhancements through the definition of new TLVs as appropriate.

The key elements of Sync-E as defined in the ITU-T Recommendations are summarized in Table 1. Further details can be found in the relevant standards.

The most significant aspect of native Ethernet communications is that the transmitter and receiver clocks are independent (free-running with frequency accuracy not exceeding ± 100 parts per million (ppm)) and are not synchronized as in TDM networks. In fact, there need be no strict timing relationship between successive frames as individual frames are separated by an idle period or at a minimum an inter-packet gap (IPG). The Ethernet transmitter delimits each packet by a start sequence ("preamble") and a stop sequence ("start-of-idle" or "end-of-stream delimiter"). At the receiver, a clock of the same nominal frequency is recovered and used to clock-in the data to a receive shift register. Only data that are bounded by the correct start and stop bit patterns are accepted.

The reconstructed receive (RX) clock can be generated, for example, using a digital phase-locked loop (DPLL) with internal local high frequency clock, frequently operating at 16 or 32 times the intended data speed. Clock generation proceeds by detecting the edge of the start bit and counting sufficient clock cycle from the high frequency clock to identify the mid position of the start bit. From there the center of the successive bits are located by counting cycles corresponding to the original data speed.

As discussed earlier, one Layer 1 method of passing high quality timing reference is to lock the Ethernet Physical Layer (PHY) symbol clock to the timing reference (primary reference clock (PRC)) as describe in G.8261 (Sync-E). However, unlike SONET/SDH or B/GPON, Ethernet does not have the requirement of a synchronous physical layer in its specification [16], so the current available standard Ethernet chipsets (native

Ethernet) have not been designed with that in mind. However, it has been rightly observed in the ITU-T recommendations that even if the Ethernet PHY has not been defined as synchronous, the IEEE 802.3 does not preclude the PHY from being made synchronous, and also being considered as a medium for distributing a reference timing signal. All it takes is for the PHYs to be locked to a high quality reference like a PRC. This is not part of the IEEE 802.3 specification [16], however, locking the Ethernet PHY does not make the implementation non-conformant, so long as the locked frequency is within the frequency range specified by the standard (±100 ppm). Other than the Layer 2+ methods, generally, the choices now available to a Telecom carrier and service provider wishing to distribute timing signals in a network are:

- Provide a separate parallel synchronization network to the existing network, which is obviously an expensive option
- Inject synchronization signals from a reference timing source into the transport medium and extract the embedded synchronization (traceable to this reference) at various points in the network (e.g., Sync-E).

A Sync-E network obviously leads to the path of having a network synchronous infrastructure but in this case without having a separate parallel synchronization infrastructure. With a Sync-E network, a carrier can rely on the Ethernet physical layers to distribute both high capacity bandwidth and reference timing signal to specific or remote parts of the network or to edge or even access equipment. A high quality reference signal could be made available at the network interfaces to synchronize local equipment as is currently done in SONET/SDH networks.

Sync-E does not come without some costs; there are some hardware implications to be considered. A network interface that needs to run synchronously would require high-quality components (oscillators, filters, etc.) in their timing circuitry (PLL) to be able to drive the physical high-speed symbol clock of an Ethernet PHY with sufficient quality. The symbol clock has to be locked to a PRC timing reference with minimal jitter and wander. The primary limitation of Sync-E is that, it does not work over any physical layer technology that is not IEEE 802.3-based such as PDH/SDH microwave, DSL, DOCSIS, etc., although it can interwork with these. Also, Sync-E unlike IEEE 1588 cannot deliver absolute time (i.e., time-of-day, wall-clock)—Sync-E provides frequency distribution only. However, the benefits of Sync-E are significant and visibly high enough to garner interest from Telecom carriers, service providers, equipment vendors, and semiconductor device and chipset vendors.

3. Synchronous Ethernet Link Architecture

Figure 2 shows a high-level architecture of a Sync-E link. The receiver derives a clock (RX Clock) which is synchronized to the transmitter clock (TX Clock). The clock is transferred as an encoded signal in the data (e.g. 4B/5B encoding for 100 Mb/s Ethernet, 8B/10B encoding for Gigabit Ethernet, etc.). This is similar to the encoded clocks used in systems such as G.703. In such encoded systems, the receiver can regenerate a copy of the transmitter clock at the receiver using a digital phase locked loop (DPLL).

It is important to not that Sync-E *cannot* be implemented over 10 Mb/s Ethernet. Also, special architectural issues have to be addressed when using Sync-E over 1000BASE-T. In fact, the 10 Mb/s Ethernet (10BASE-T) is not even capable of synchronization signal transmission over the physical layer interface because a 10BASE-T transmitter stops sending pulses during idle periods. A 10BASE-T transmitter simply sends a single pulse, keepalive pulse, every 16 ms to notify its presence to the receiving end [16]. Of course, such infrequent pulses

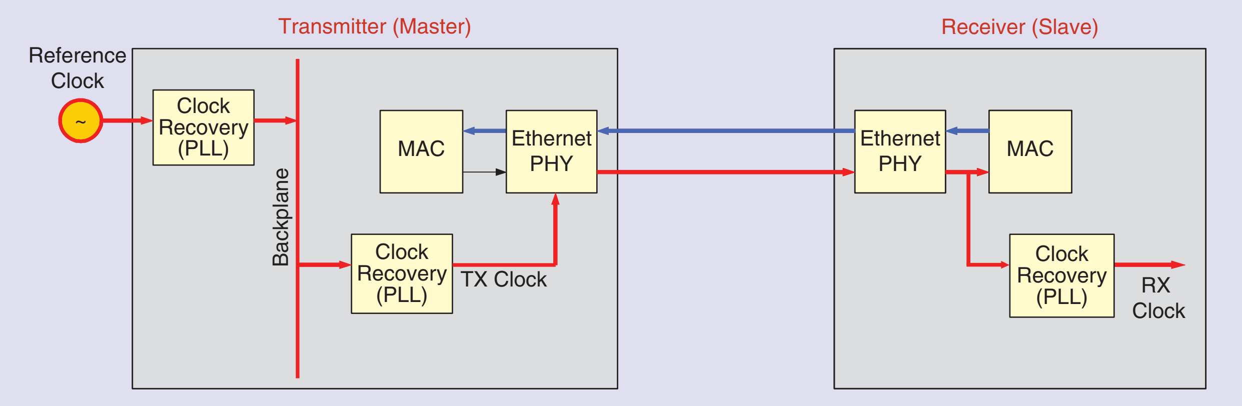

Figure 2. High-level architecture of a Sync-E link.

are not sufficient for clock recovery at the receiver. Idle periods in faster Ethernet flavors (100 Mb/s, 1 Gb/s and 10 Gb/s) are continuously filed with pulse transitions, allowing continuous high-quality clock recovery at the receiver--good candidates for Sync-E.

The Sync-E architecture has the advantage that the timing information is accurately aligned to the received data. It also has the advantage that the receiver tracks any clock drift which may arise, for instance due to temperature variation, when the timing reference is the transmitter local oscillator. A Sync-E setup distributing timing from a PRC will require high-quality components (oscillators, etc.) to construct a PLL of sufficient quality to run the physical high-speed symbol clock of an Ethernet PHY locked to the PRC timing reference with minimal jitter and wander. The penalty of deploying Sync-E is that more elaborate timing paths must be provided in the Ethernet network. Sync-E switches and networks will require a bit more complex Ethernet interface designs, and potentially require more configuration since there are many more interface options, and also because timing loops much be avoided (Figure 3). However, despite these concerns (which are easily surmountable based on many years of SONET/SDH principles and experience) Sync-E allows timing to be distributed over packet networks and allows interworking with legacy TDM devices (Figure 4).

4. Some Applications of Synchronous Ethernet

Sync-E operates on the physical layer, effectively taking many of the SDH synchronization mechanisms over into the packet world. Also, Sync-E timing distribution operates independently of the network load. In this section we describe some important emerging applications of Sync-E, applications which could harness the high data transfer and timing distribution capabilities of Sync-E. We also attempt to show the synergy and possible interworking between Sync-E and traditional TDM services.

4.1. Circuit Emulation Services (CES) over Synchronous Ethernet

Many organizations have offices in different locations, both domestic and international. Leasing E1 or T1 lines for TDM services connectivity at each branch and office location can be very expensive. Institutions can save

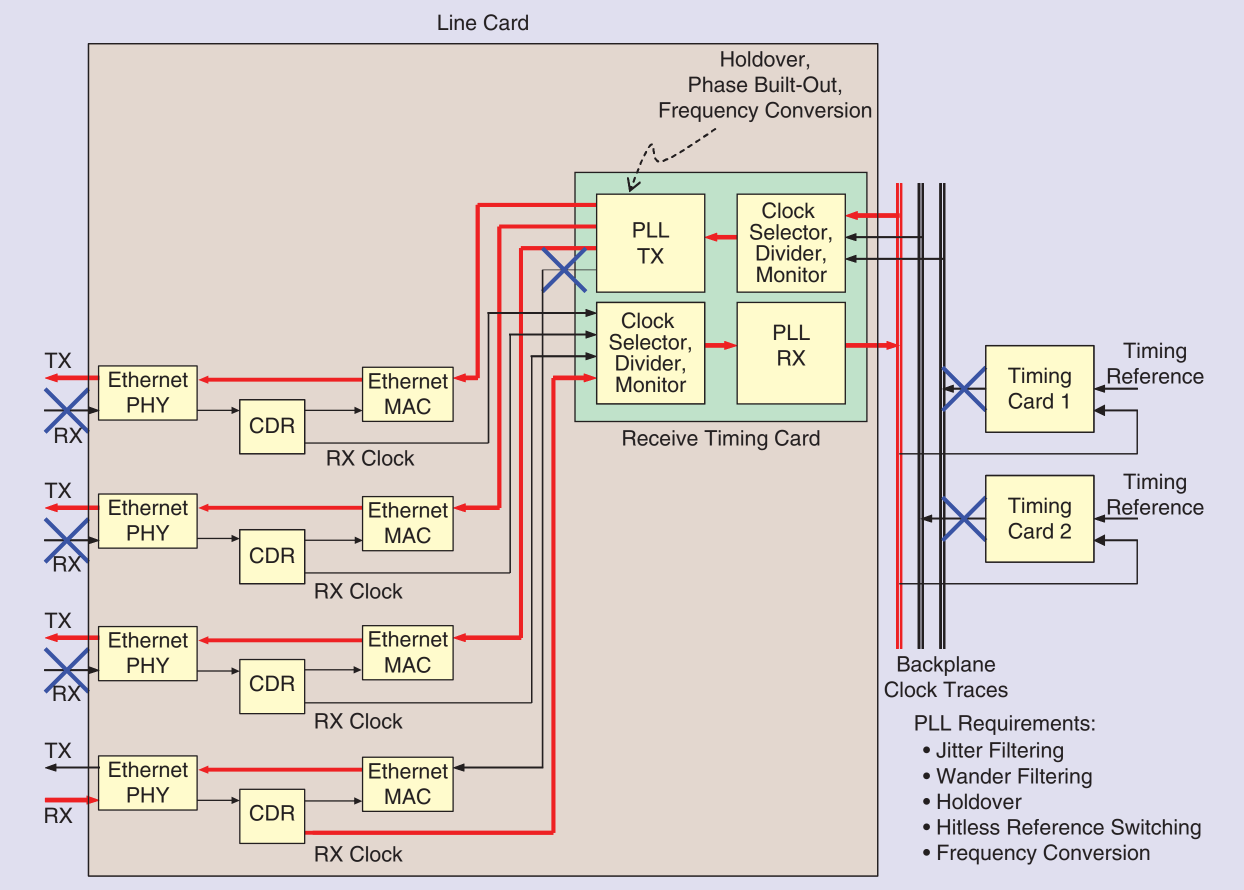

Figure 3. Example clock distribution paths in a carrier-grade Sync-E line card.

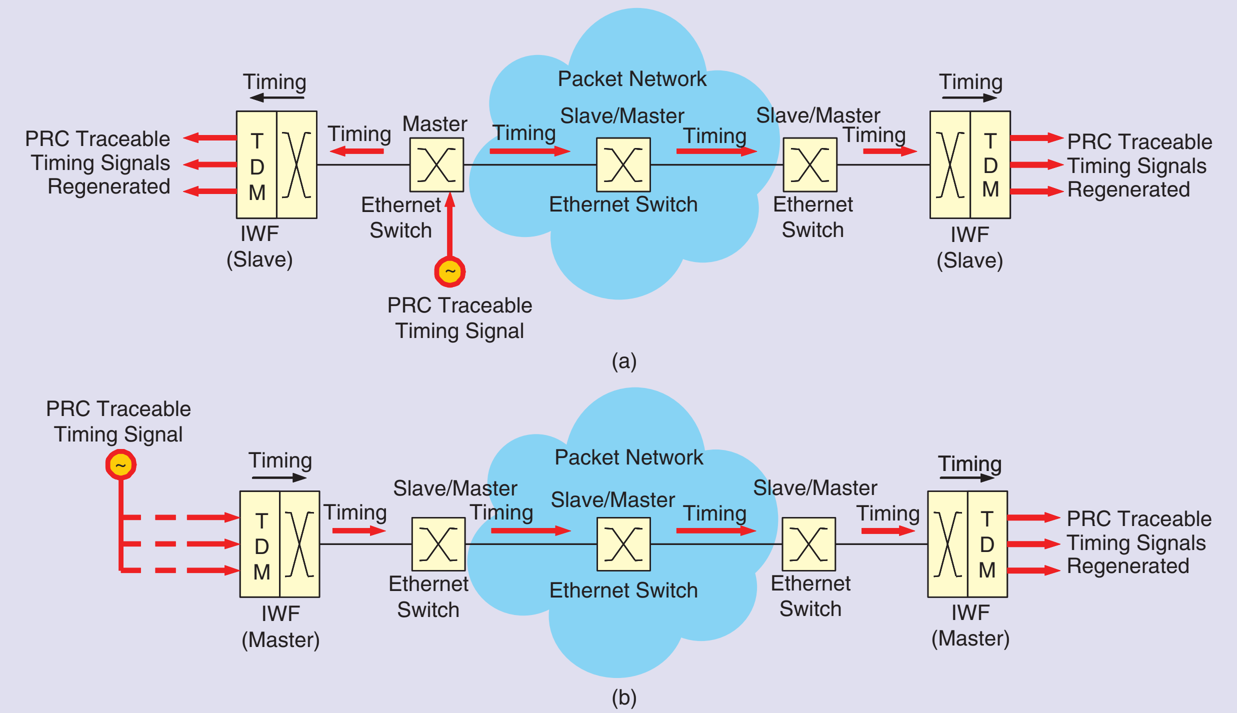

Figure 4. Example timing applications of Sync-E. (a) Timing from a PRC and (b) line timing.

on leased line costs by emulating E1/T1 trunk connections between remote locations across relatively low-cost, high-speed Sync-E. This application of CES allows users such as multi-site enterprise, government offices, universities, school districts, and remote call centers to interconnect their distributed TDM systems over packet networks [15], [19]. This creates a converged network where local governments, educational institutions and multi-location enterprises are able to take advantage of low-cost Ethernet Metropolitan Area Networks (MANs) for data connectivity between agencies, branches and institutions. In many cases these organizations are also paying for leased E1/T1 lines for voice trunking between locations. Also, using CES over Sync-E a carrier can upgrade to a Sync-E network whilst still maintaining their existing TDM business.

Figure 5 illustrates CES over Sync-E where TDM devices are transparently interconnected across a Sync-E network. We see that since the timing transfer is inherently provided by the Sync-E network, the interworking function (IWF) will consist only of a CES module that provides TDM/Ethernet encapsulation and decapsulation functions.

The main benefits of CES over Sync-E are:

- it protects investments in existing TDM-based systems,
- it reduces or eliminates bandwidth and leased-line costs while maintaining high clock qualities,
- it is transparent to all TDM features and signaling protocols since the TDM bit stream is carried transparently across the Ethernet network,
- and, it supports true convergence of voice and data services over packets networks (all traffic including TDM can be transmitted over a single Ethernet transport network, without having to build network infrastructures tailored to each type of user traffic).

4.2. Wireless Backhaul over Synchronous Ethernet

Wireless backhaul refers to the provisioning of transmission and transport facilities over a variety of transport networks for connecting base stations to the wireless operator's core network and switching centers. High backhaul costs have become one of the major contributors to the costs of building and running mobile networks. Such high backhaul costs have driven mobile providers to consider newer backhaul strategies (Figure 6).

4.2.1. Today's Picture

In a majority of today's mobile networks, the base stations (GSM BTS, UMTS Node B) have E1/T1 access lines carried over ATM or SDH/SONET transmission facilities. To reduce costs and number of E1/T1 access lines, backhaul or aggregation is traditionally implemented in

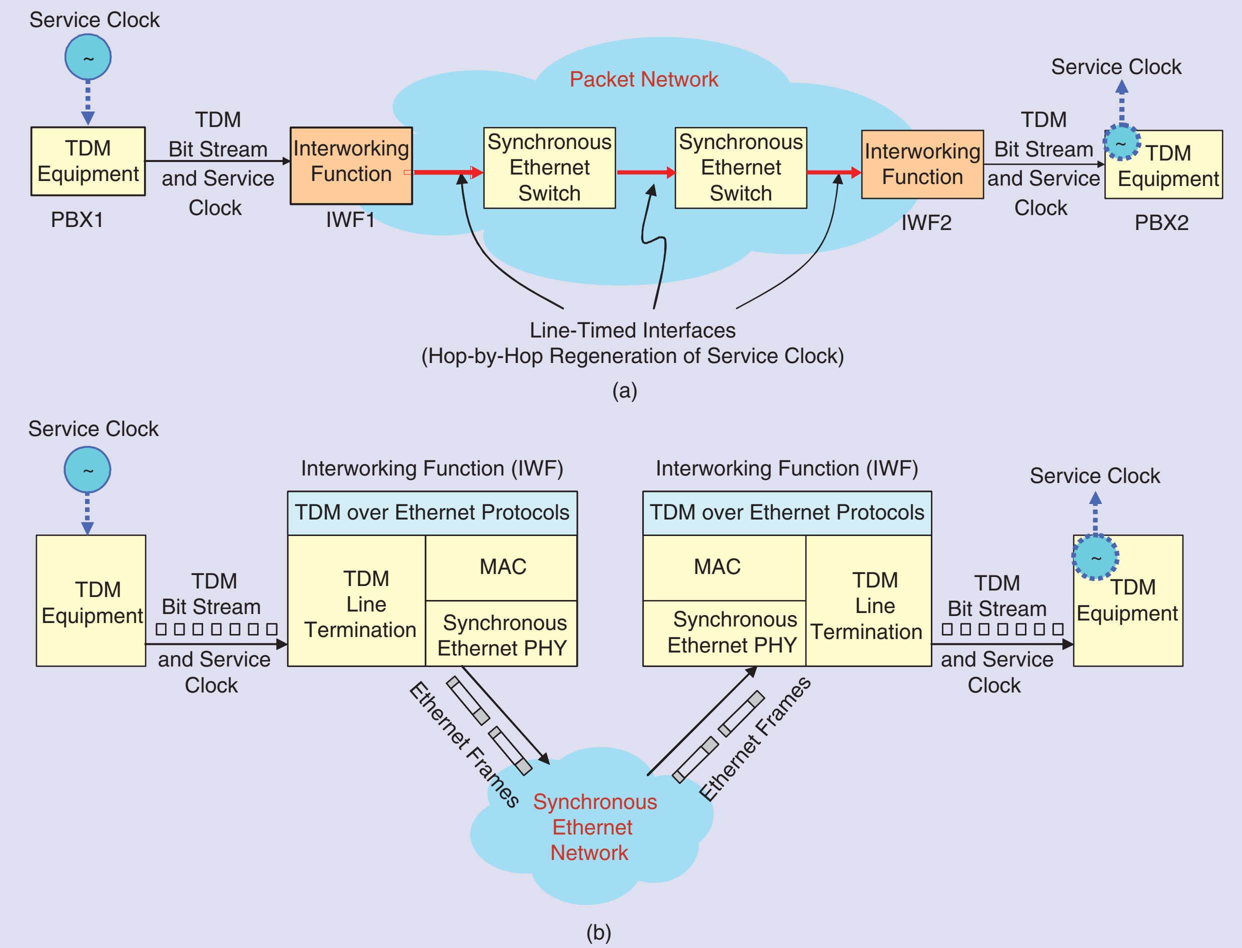

Figure 5. Circuit emulation services (CES) over Sync-E. (a) Timing chain in Sync-E and (b) interworking functions in the data and timing path.

high-density segments of the operator's core network, such as the Base Station Controller (BSC) or the Mobile Switching Center (MSC). This allows several E1/T1s to be aggregated together and then utilizing statistical multiplexing to transport them over STM-1/OC-3 lines. Aggregation in this case then becomes an essential part of existing mobile network transport design because it allows for more efficient use of the transport bandwidth and simplifies network management.

With the introduction of 3G (UMTS, HSPA, HSPA+), LTE, and WiMAX, the mobile world is evolving into a real multimedia environment. Instead of plain voice services, a wider range of services is available to subscribers. This range embraces delay-sensitive and high quality services like video streaming (which require a reserved backhaul bandwidth (constant rate)) to best effort-type services like Internet surfing, back office services, mailing, data downloads, etc., (which, by nature, are statistical).

The question that easily comes to mind is, is it possible to serve more mobile subscribers with diverse user requirements and bandwidth requests using the same infrastructure? Such high capacity performance, however, comes at a price: an exponential increase in the bandwidth required to backhaul mobile traffic from base stations to the wireless switching centers (GSM BSC, UMTS RNC).

From industry trends we see that mobile operators are saddled with bewildering choices of backhaul technologies as they try to anticipate which backhaul infrastructure will best serve their current and future requirements. The easiest but naïve decision would be to build out parallel networks—using a dedicated transport network for each different mobile generation. However, this is not as efficient or potentially cost-effective approach as integrating diverse traffic streams over a single backhaul technology.

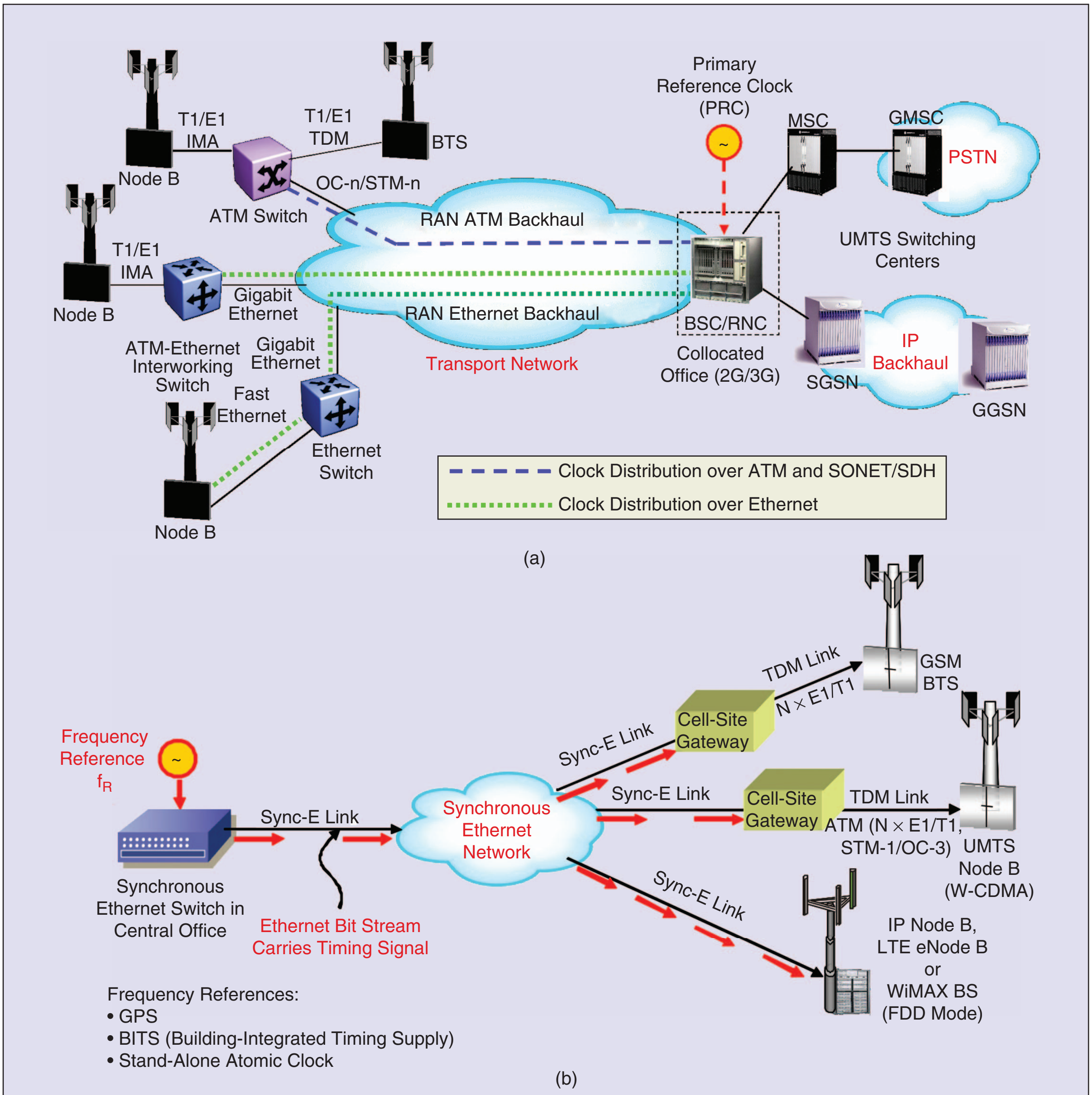

Figure 6. Mobile wireless backhaul. (a) Backhaul of GSM and UMTS services and (b) wireless backhaul over Sync-E.

Given the above concerns, mobile operators are looking for converged backhaul access network solutions that are technologically feasible, economically sound and readily available. The challenge is that the explosive increase in backhaul waiting down the road must be controlled to ensure profitable mobile service provider operations. Reference [18] provides a much detailed discussion on synchronization aspects and the state of the art on GSM and UMTS wireless backhaul solutions. More recent discussions on mobile backhaul can be found in references [31]–[34].

4.2.2. Current Trends and Problems

Before we proceed further in our discussion, let us examine a number of current trends that have complicated the mobile backhaul picture:

- While we may say one or two E1/T1 lines of the transport network would be sufficient to handle the average number of links connected to 2G cellular base stations, the impending introduction of newer 3G and other wireless services (both fixed and mobile) may require this number to increased significantly at each cellular site. It is not

Synchronization is crucial for mobile wireless networks because the radios used in these networks operate in very strict bands that need separation to avoid channel interference which reduces the call quality and network capacity. Poor synchronization has also negative impact for the hand over between base stations.

uncommon to hear numbers from 8 to 16 E1/T1 per site. Without mechanisms in place to control operating and capital expenses (Opex and Capex), the costs may not justify the business case.

- One may argue that 3G data traffic and other advanced fixed and mobile services are still only a relatively small overall portion of mobile transmission, but this situation is changing quickly as wireless operators expand their networks and services over the next few years. Assuming that additional E1/T1 lines are readily available from the wireline operator, the amount of backhaul traffic is predicted to grow faster than the expected average revenue per user.
- Complicating the picture is the need to support simultaneously the divergent technological demands and applications of existing 2G/2.5G networks, emerging 3G operations, and emerging LTE and WiMAX, and 4G wireless services. The transition of backhaul networks from TDM circuit-switched to ATM and, eventually, Gigabit Ethernet/IP/MPLS packet switched networks raises new challenges, particularly regarding the cost and suitability of the access network to handle and manage efficiently increased bandwidth capacity and the complexities of voice and data in a converged network.

This new era of 3G and other emerging 4G wireless services presents additional challenges to network designers. As a result, aggregation and backhauling, which characterizes existing ATM or SDH/SONET core networks, also now has become an essential building block in the radio access and transport networks.

4.2.3. Looking at the Synchronous Ethernet Backhaul Option

Mobile networks, by design, require a high quality level of clock synchronization to maintain a proper service quality. Synchronization is crucial for mobile wireless networks because the radios used in these networks operate in very strict bands that need separation to avoid channel interference which reduces the call quality and network capacity. Poor synchronization has also negative impact for the hand over between base stations.

Clock synchronization is achieved by distribution of a timing reference signal among the numerous base stations spanning the network. Packet networks, however, are asynchronous and statistical-based by nature and do not provide inherent timing information whatsoever. This situation is further complicated in a packet switched networks (PSN) because of the presence of packet loss and packet delay variation (PDV). This situation then calls for sophisticated clock recovery mechanisms to reconstruct timing and achieve the desired timing accuracy in the presence of packet loss and PDV when Layer 2+ methods are used. But since Sync-E is designed with accurate timing as an embedded requirement, the drawbacks of using Layer 2+ packet network timing solutions as part of the backhaul solution are avoided.

Sync-E provides an effective solution to connect the installed base of mobile infrastructure (which has both GSM TDM-based and UMTS ATM-based network elements) over Ethernet. The emergence of Sync-E could enable mobile operators to exploit the full potential of these technologies by offering mobile backhaul services at competitive costs. Sync-E is, however, not the complete answer, since a full solution also requires the use of pseudo-wire technology (for example CES), which transports TDM/ATM circuits transparently across Ethernet, IP or MPLS packet networks. Pseudo-wire solutions are particularly suited to cellular backhaul because they are transparent to the underlying PSN technology.

By applying appropriately CES over Sync-E, mobile operators will be able to speedily deploy high capacity wireless services and keep operating costs to a minimum while increasing their revenues and profitability from media-rich 3G content. Although the mobile backhaul challenge opens a door for new solutions to be incorporated in the transport network, such as packet-based technologies, Sync-E could prove to be a technology enabler for such a migration.

4.3 Differential Timing Transfer over Synchronous Ethernet

Differential timing transfer is used when there is a network interface with its own reference source clock (the service clock) and there is the need to transfer this clock over a core packet network (with its own independent reference clock) to another interface. This transfer is done while both network interfaces and the core network maintain their timing traceability to their respective independent reference source clocks [3]–[7]. This section explains why implementing differential timing transfer over a Sync-E network (with its own embedded timing reference) is an important timing distribution option for Telecom carriers and service providers (Figure 7).

Differential timing can be an effective method to control jitter and wander in CES applications by providing a PRC or network traceable reference timing signal at each interworking function (IWF) (Figure 7). This method of passing a service clock over the Ethernet network involves locking the Ethernet PHY symbol clocks of the Sync-E network to a common timing reference (a PRC). It is assumed that the Sync-E network has implemented all the necessary requirements of a synchronous physical layer into it end-to-end (i.e., IWF-to-IWF) as specified by the relevant ITU-T recommendations [13]–[15].

In Figure 7, the physical layer (all Ethernet PHY) clocks of the Sync-E network operate synchronously to the PRC (network clock), and timing control packets encoded with differential timing information representing the characteristics of the service clock are sent over the Sync-E network from source IWF to the receiving IWF. At the receiving IWF, the Ethernet PHY symbol clock which is also traceable to the PRC can be used in conjunction with the received timing control packets to reconstruct the service clock.

Differential timing over Sync-E can offer a robust solution to address the transport of timing signals in wireless backhaul applications such as GSM and UMTS. Reference [6] describes one example of differential timing suitable for deployment in general packet networks (Ethernet, IP, MPLS, etc.). This method is much more general and flexible that the ATM-specific method of Synchronous residual Time stamps (SRTS) [4], [5].

4.4 Synchronous Ethernet as a Packet Backplane Interconnect for TDM Modules

Sync-E can be used to replace the TDM backplane infrastructure in applications as diverse as voice over IP gateways, telephone switches and conventional computer telephony (CT) systems. Some of the advantages of using a packet backplane are; it uses readily available and low cost network hardware, it is easily scalable (simply increase Sync-E switch port density to scale application), and it eliminates the timing problems in passing large TDM buses around the system. Figure 8 shows a multi-service access platform with a Sync-E backplane.

Some vendors have PBXs with distributed architectures where the PBXs components are not collocated at one place. This architecture allows the PBX capabilities to be distributed between enterprise sites, while abiding to central configuration guidelines. With a Sync-E backplane, the distributed PBX's remote shelves, also known as line interface modules (LIMs), are inter-connected via the Sync-E switch. The Sync-E switch will be responsible not only for this connection, but also for distributing software and configuration to the LIMs, and for performing backup operations. Obviously, without the Sync-E switch (backplane), these connections would require expensive E1/T1 leased lines.

This architecture also allows the use of a packet switched backplane within a variety of WAN access/edge equipment. It allows systems vendors to migrate in stages from a pure TDM backplane to a Packet Switched Backplane, without the need to completely redesign each of the line and resource cards. Through the use of the packet switch, the device can support both a 'distributed' and 'centralized' system architecture. This architecture

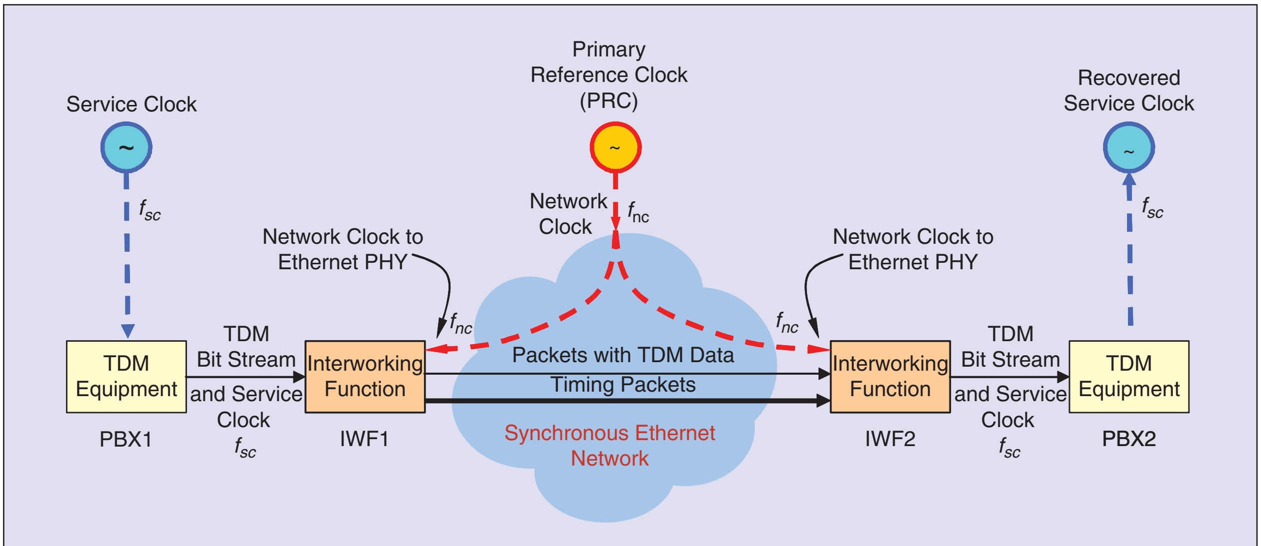

Figure 7. Differential timing transfer over Sync-E.

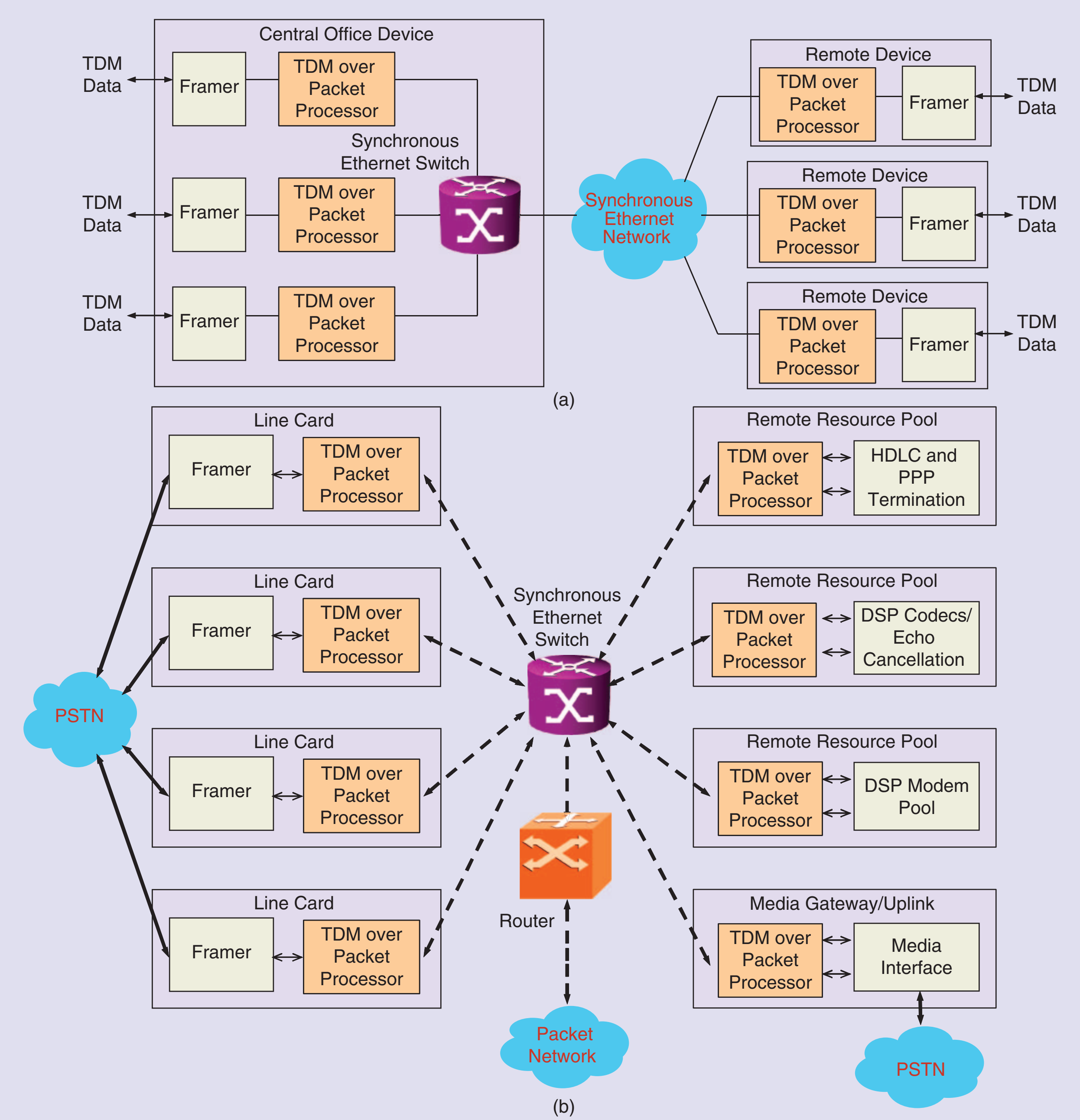

Figure 8. Sync-E as a backplane interconnect for telecommunication systems. (a) Remote device attachment to central office over Sync-E and (b) Sync-E as a backplane interconnect for TDM modules.

allows systems vendors to take advantage of cost effective packet switched backplanes while at the same time making full use of its scalability—a significant advantage when faced with the ever increasing volumes of traffic.

4.5 TDM Backplane Extension over Synchronous Ethernet

Assembling computer telephony (CT) systems involves integrating hardware and software modules that collectively provide all of the desired functionality. CT systems integrate voice, fax, and data networking. CT hardware components are typically packed as add-in boards which communicate with other boards in the system using a CT bus. H.100 and H.110 CT buses are high capacity, fault tolerant CT buses that allow many streams of media data (e.g., phone call data) to pass between boards simultaneously.

TDM buses such as the H.100/H.110 bus commonly used in today's CT systems are typically based on a physical backplane approximately equal to the width of a single standard telecom rack. H.100 and H.110 are non-proprietary switch fabric implementations developed by the ECTF (Enterprise Computer Telephony Forum). H.100 and H.110 standards defined what is required to implement a CT Bus on PCI and CompactPCI systems. H.100 is for PCI, the common bus for desktop computer systems, while H.110 is for CompactPCI, which is considered industrial-grade PCI.

H.100/H.110 integrates TDM capabilities with PCI and CompactPCI bus architectures. The TDM bus carries real-time voice and fax traffic across a TDM bus that implements 4096 bidirectional time slots (64 kb/s each). The bus can support up to 2048 full-duplex calls. H.110 is built right into the CompactPCI backplane, while H.100 is implemented as a ribbon cable connecting the different CT boards. The main features of the H.100 and H.110 buses are given below:

- **H.100:** This is a hardware specification that provides all necessary information to implement a CT bus interface at the physical layer for PCI computer chassis card slot (independent of software applications). It is the first card-level definition of the overall CT Bus single communications bus specification. This CT bus is a bit-serial, byte oriented, synchronous, TDM transport bus operating at 8.192 MHz. It consists of two clocks, two frame sync pulses, one backup network timing reference, and 32 independent bit-serial data streams. Voice/data transfer on the bus is accomplished by assigning one or more time slots numbers and bus stream numbers to the sender and receiver(s). At the selected time slot, the software-selected sender drives the bus and somewhere on the bus, the receiver(s) clock in data bits. The H.100 specification documents CT Bus Clocks and Synchronization; data bus lines, interface device requirements, data bus timing, clock skew, reset, power on, and other timing requirements; electrical specifications, mechanical specifications including the design and location of connectors, pin assignments, PCB layouts, and cable requirements; support for partial implementations and optional signals; and inter-operation with other buses.
- **H.110**: The H.110 specification is functionally identical to the H.100 specification. However, some of the features in H.100 relating to high availability realize their full utility only in the hot swap CompactPCI environment. There are electrical differences between H.100 and H.110 due to the differences between a ribbon cable and a backplane implementation. The H.100 CT bus uses ribbon cables and special connectors to physically connect CT boards inserted into a common PCI bus. The H.110 is a version of CT Bus for CompactPCI chassis where the bus signals travel through the backplane rather than ribbon cable. In addition to the features of H.100, it supports hot swapping of boards, increased reliability, and up to 20 slots.

Extending the reach of the CT bus is expensive using traditional TDM infrastructure. Such links are not easily scalable, and require accurate and stable clock generation. Sync-E with CES capabilities enables the CT bus to be simply and easily extended beyond confines of the rack. This enables the entire bus to be replicated in another physical location using low cost, flexible and easily managed connection medium like Sync-E. Figure 9 illustrates TDM Backplane Extension over Sync-E with Circuit Emulation capability.

Figure 10 is an application of TDM backplane extension in a remote access concentrator. The remote access concentrator is an example of the equipment being designed today to enable TDM voice and modem services to be sent over packet networks. Within these systems, the TDM backplane extension solution with circuit emulation capabilities allows the access concentrator

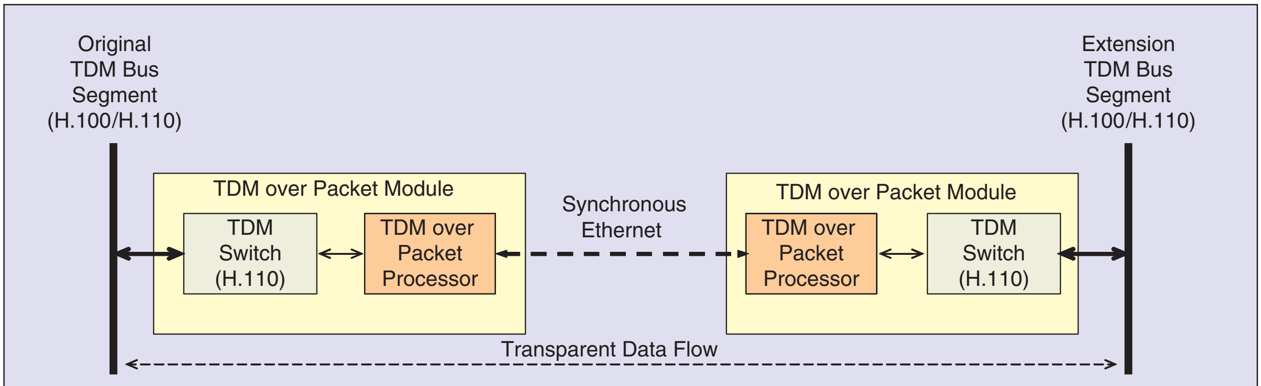

Figure 9. TDM backplane extension over Sync-E.

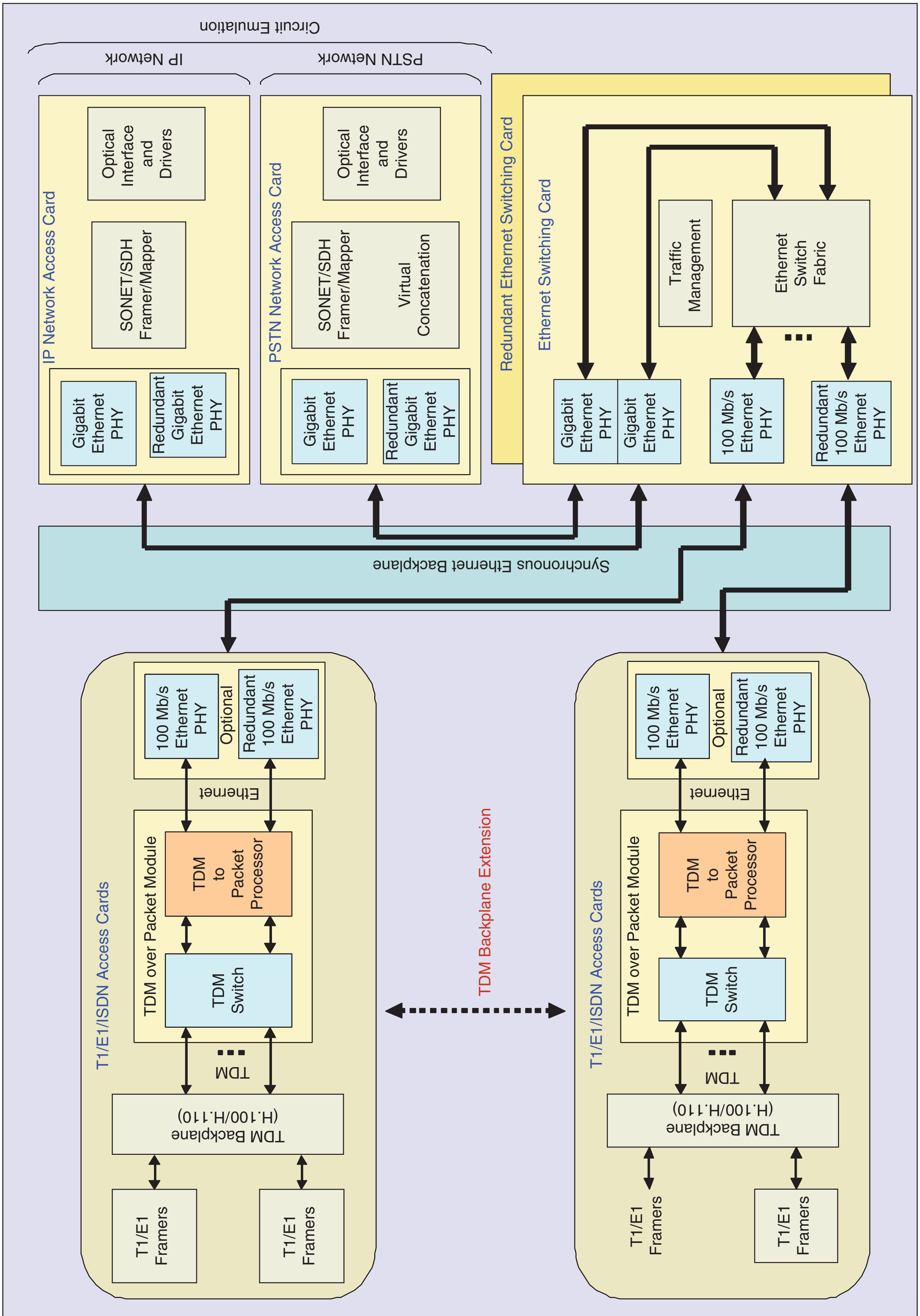

Figure 10. Example application of TDM backplane extension over Sync-E with circuit emulation capabilities.

Sync-E allows systems companies to take advantage of cost effective packet switched backplanes while at the same time making full use of its scalability—a significant advantage when faced with the ever increasing volumes of traffic.

to serve as a complete WAN access interface, able to support packet reception, TDM packet assembly, timing distribution, CPU packet generation and packet transmission. These concentrator devices typically includes several features to optimize handling of voice and data traffic; an integrated digital TDM switch, 100 Mb/s Ethernet MAC, configurable packet management and Stratum 4E PLL.

Sync-E technologies allows the use of a packet switched backplane within a variety of WAN access/edge equipment. They allow systems companies to migrate in stages from a pure TDM backplane to a Packet Switched Backplane, without the need to completely redesign each of the line and resource cards. Through the use of the integrated digital TDM switch, the device can support both a "distributed" and "centralized" system architecture. Sync-E allow systems companies to take advantage of cost effective packet switched backplanes while at the same time making full use of its scalability—a significant advantage when faced with the ever increasing volumes of traffic.

4.6 TDM Backplane Expansion over Synchronous Ethernet

One of the issues faced by medium and high-end telecommunication systems is scalability. The H.100/H.110 TDM bus is limited to 4096 concurrent time slots, or 2048 full duplex links. Sync-E with structure-aware CES capabilities [17], [20] can be used to expand the capacity of a system by switching time slots between multiple separate TDM backplane segments. Figure 11 shows TDM backplane expansion using Sync-E. Unlike parts based on expensive or proprietary infrastructure, the use of Sync-E switch fabric enables common, readily available and low cost hardware to be deployed, reducing both installation costs and operational expenses. The combination of

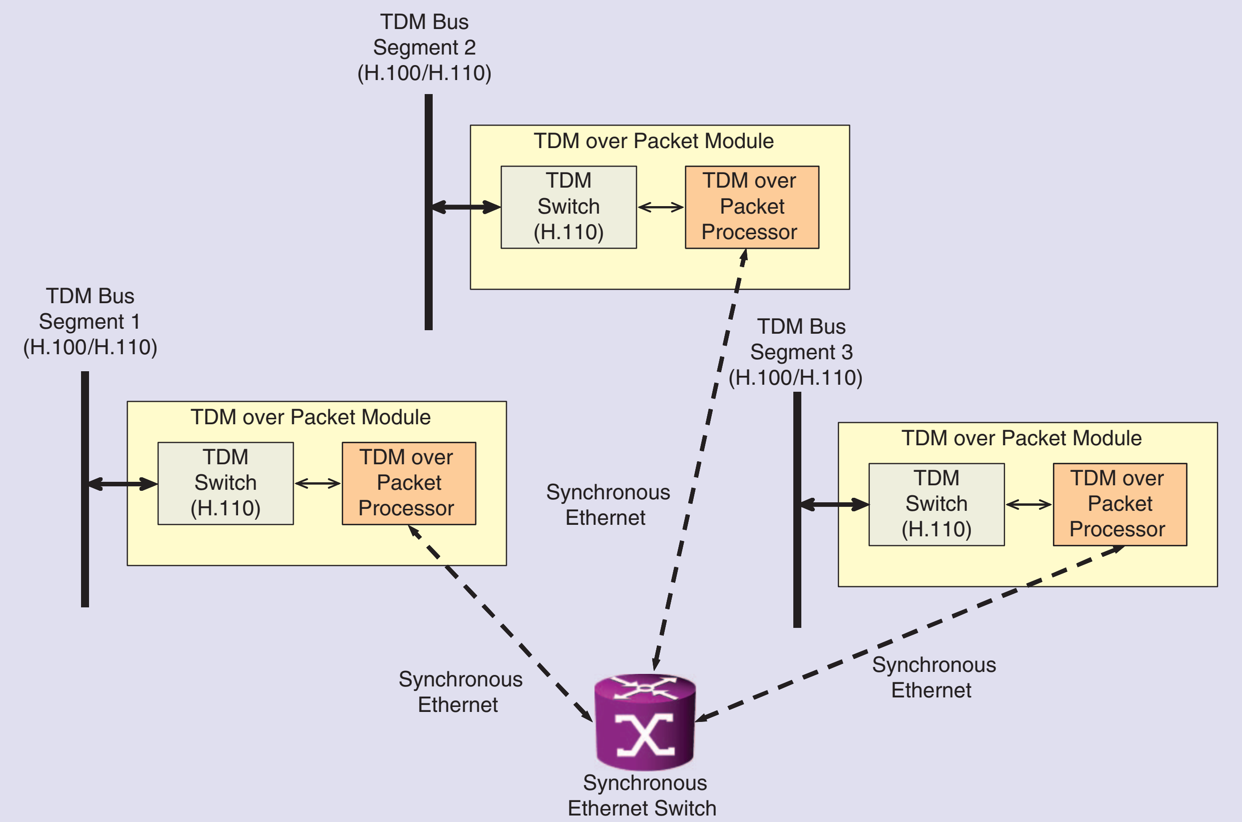

Figure 11. TDM backplane expansion over Sync-E.

existing TDM infrastructure and a Sync-E packet backplane enables systems to be built up using off-the-shelf components, and to be quickly expanded as required.

Clocking using Sync-E allows the clocks at each end of the packet backplane and the TDM interfaces to be traceable to a common reference signal. Sync-E provides a simple way of achieving a completely synchronous backplane operations since reference timing is transparently propagated to all TDM interfaces in the backplane as shown in Figure 11.

As illustrated in Figure 12, Sync-E with structure-aware CES capabilities allows the splitting of a TDM backplane segment frame into multiple N*64 kb/s circuits and transmitting those circuits across different structured CES sessions to one or multiple destinations. This allows, for example, a single user to communicate with multiple remote users.

Similarly, circuits from many different TDM backplane segments can be routed to a single TDM backplane, where the various circuit timeslots are interleaved to form an outgoing TDM backplane frame. Thus, TDM time slots can be combined in highly flexible way for transport across the packet backplane. Time slots on a TDM backplane segment at one end of the packet backplane can be mapped into different destination TDM backplane segment time slots at the other end of the packet backplane. Mapping TDM backplane segment time slots requires that the total number of time slots mapped at each end of the packet backplane matches. Essentially, the Sync-E switch with structure-aware CES capabilities in this case functions in the same way as a classic digital access and cross connect system (DACS).

5. Conclusion

This paper has described Synchronous Ethernet and some of the emerging applications of this highly accurate timing distribution method. While TDM networks inherently deliver synchronization timing signals along with the data, packet networks (Ethernet, IP, MPLS) which are generally asynchronous do not transfer any synchronization timing information whatsoever. With the convergence to packet networks, there are still a significant number of applications that require accurate synchronization timing signals to be distributed over the packet networks. The move to packet (IP, Ethernet, MPLS) will eliminate the option for devices to derive accurate synchronization signals from the network. Telecom carriers and operators will need to move to “packet

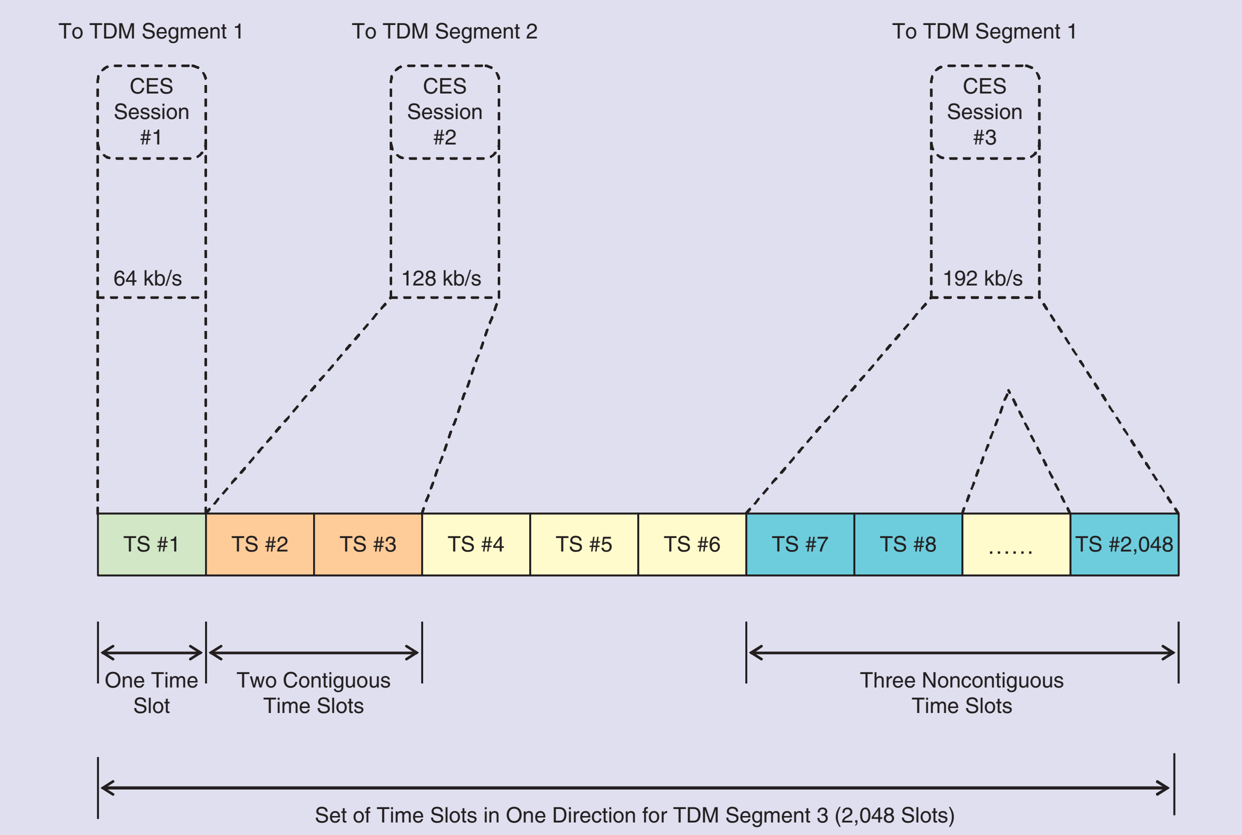

Figure 12. Switching time slots between multiple separate TDM backplane segments.

friendly" sources of synchronization to meet their synchronization requirements. Thus, a key dependency in the evolution to packet networks in telecom networks is the ability to deliver carrier grade synchronization over packets to remote wireless base stations and access platforms. The ITU recently defined Synchronous Ethernet (in ITU-T Recommendations G.8261, G.8262, G.8264) to address the need for delivery of frequency synchronization over Ethernet transmission networks. Sync-E operates on the Physical Layer (PHY), effectively taking many of the SDH/SONET synchronization mechanisms over into the packet world. Thus, with timing transfer occurring at the physical layer, Sync-E operates independently of the network load.

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